TITLE OF THE INVENTION

Scanning stylus Atomic Force Microscope with cantilever Tracking and Optical Access

~~ATOMIC FORCE MICROSCOPE AND METHOD OF OPERATING AN ATOMIC~~

~~FORCE MICROSCOPE~~

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BACKGROUND OF THE INVENTION

Field of the Invention

The present invention relates to scanned-stylus atomic force microscopes and a method of operating a scanned-stylus atomic force microscope, and in particular to large scan optical lever atomic force microscopes.

Discussion of the Background

Atomic force microscopes (AFMs) are extremely high resolution surface measuring instruments. The AFM is described in detail in several U.S. Patents including 4,935,634 to Hansma et al, 5,025,658 to Elings et al, and 5,144,833 to Amer et al. The AFM scans a stylus mounted on a flexible spring lever (cantilever) with respect to a sample. The actual motion can be produced by translating either the sample or the stylus and cantilever. This motion can be produced by any scanning mechanism, but is typically produced by a piezoelectric translator. All generic scanning mechanisms will be referred to as scanners.

Surface features on the sample interact with the stylus and cause the cantilever to deflect. By measuring the deflection of the cantilever as a function of position over

the surface, a map of the surface can be created. In practice, it is often necessary to minimize the force that the cantilever applies to the surface. For this reason, AFMs are usually run under feedback in the "constant force mode." In this mode, the cantilever deflection is kept constant during imaging by moving either the cantilever or the sample with respect to each other. The sample surface is then mapped out by reading a signal indicating the relative motion of the cantilever or sample needed to keep the cantilever deflection constant. When a feedback system is used to keep the cantilever deflection constant, this deflection (and hence force on the sample surface) can be held at a minimum value.

There are also a variety of AC modes where the cantilever is vibrated and features of the sample are sensed by measuring the amplitude, phase, or frequency of the vibrating cantilever. See for example copending Application serial no. *now U.S. patent No. 5,412,980* 07/926,175 entitled An Ultra Low Force Atomic Force Microscope by Elings and Gorley.

The first atomic force microscopes used the principal of electron tunneling to detect minute deflections of the cantilever. More recently, two groups (Meyer and Amer, Appl. Phys. Lett., 53 (24), Dec. 12 1988 and Alexander et al, Appl. Phys. Lett., *65, 1 January 1989)* ~~53(12), Sep. 19, 1988~~ independently succeeded in using the "optical lever technique" to measure cantilever deflections with subnanometer resolution. The "optical lever" technique works in the following way.

Referring to Fig. 1, a prior art AFM system is illustrated. An AFM cantilever 14 is made so that it is sufficiently reflective that it can act as at least a partial mirror. A laser beam 17 from a laser 10 is focused onto one side of the AFM cantilever 14 having a stylus 15 mounted thereon. Laser beam 14 passes through or alongside a scanner 12 using lens 11 and the reflected beam 18 is directed to a position sensitive detector 16, usually a multi-segment photodiode. Cantilever 14 is attached to a mounting substrate 20, which is attached to scanner 12, or to an optional mounting element 19. A cantilever deflection changes the angle of the cantilever with respect to the incoming laser beam 17 and thus moves the reflected laser beam 18 on the position sensitive detector 16 as the cantilever 14 is scanned over the sample 13.

Prior art scanned-stylus AFMs as shown in Fig. 1 focus a laser spot onto one side of a cantilever and then the scanner moves the cantilever over the sample. Since the cantilevers are typically a few hundred microns long and a few tens of microns wide, the focused laser spot must be only 10-30 microns in diameter so that laser light does not spill around the cantilever and onto the sample. If laser light spills around the cantilever, the AFM's sensitivity and therefore vertical resolution is decreased. Also the position sensing photodiode may be disturbed by optical interference from the sample. This means that if a prior art scanned-stylus AFM

scans the cantilever more than 10-30 microns, the cantilever will move out from under a stationary laser beam, and the AFM's performance will deteriorate. There is great interest in scanned-stylus AFMs that can scan in the range of 100 microns, much larger than the range of this prior art AFM.

The majority of AFMs that have been built scan a small sample under a fixed stylus and cantilever. There is, however, great interest in AFMs that scan the stylus over a fixed sample. This method has a number of advantages, including the ability to image samples that are too large to be scanned easily. A number of scanned-stylus AFMs have been built and described in the literature. For example, such instruments have been built by G. Meyer and N.M. Amer, Appl. Phys. Lett., 56, p. 2100 (1990), C.B. Prater et al., J. Vac. Sci. Technol., B9, p. 989 (1991), Hipp et al, Ultramicroscopy 42-44, p. 1498 (1992), Putman et al, presented at the OE/LASE '93 Conference, January 19, 1993, Los Angeles, CA, Baselt and Baldeschweiler Rev. Sci. Instrum. 64, p.908 (1993), Clark and Baldeschweiler Rev. Sci. Instrum. 64, p. 904, (1993), and by Digital Instruments, U.S. Patent 5,025,658 (E.g., Stand Alone™ AFM, Large Sample Scanning Probe Microscope) assigned to the assignee of the present application.

All of the previous instruments suffer from compromises that do not allow them to take full advantage of the capabilities of AFMs that scan by moving the samples instead of the stylus. Prior art scanned-stylus AFMs that use a fixed

laser to measure cantilever deflection have a maximum scan size set by the diameter of the laser beam at the cantilever. If the cantilever is scanned a distance larger than the beam size, it will move out from under the beam, and it will no longer be possible to detect the cantilever motion.

A small number of optical lever scanned-stylus microscopes have been built by using a laser beam that is defocused so that in the plane of the cantilever, it is larger than the desired scan range of the cantilever. Microscopes of this type have been built separately by Meyer et al, *supra*, C. B. Prater et al. *supra*, Hipp et al, *supra*, Baselt et al, supra, and Clark et al, *supra* and are typically of the type shown in Fig. 1. The performance of this type of scanned-stylus AFM is greatly diminished at scan ranges of larger than 10-20 microns. This performance loss is seen in the form of images that appear "warped" and uncontrolled force variation across the scan field. These effects have been recently described by Baselt et al, *supra*.

The reason for this performance loss is as follows. Scanned-stylus AFMs often use a piezoelectric tube translator (12 in Fig. 1) to scan the cantilever over the sample. Typically, one end of the scanner is held fixed and the other end performs the scanning pattern with a pendulum-like motion. This means that scanning the cantilever over the sample surface changes both the angle and position of the cantilever with respect to the incoming laser beam and the angle and

position of the cantilever with respect to the position sensitive detector. Some of these problems are described in the paper by Hipp et al, *supra*. In addition, some commercial cantilevers are not flat, but are instead warped by a small amount. Even in the case that the cantilever motion is small enough that the laser stays on the cantilever, the deflection of the reflected beam can change by large angles as the laser moves on this warped surface. For example Baselt et al, supra, measured false cantilever deflections of 45 nm while scanning a warped cantilever only 750 nm under a fixed laser.

The net result of these angular and position changes is to move the reflected laser beam across the position sensitive detector. In "constant force mode" operation, however, the position of the laser beam on the detector is held constant with a feedback loop that moves the cantilever with respect to the sample. So changes in the relative angles and positions of the laser, cantilever, and detector will cause the feedback loop to exert more or less force on the surface as the cantilever is scanned to keep the position of the laser constant on the detector. These force variations can be very destructive. Many biological samples cannot be imaged with forces larger than one nanoNewton (nN). See for example Hoh and Hansma, Trends in Cell Biology, 2, p. 208 (1992). In the above case, where a warped cantilever caused a false deflection of 45 nm over a 750 nm scan, the force variation could be as high as 1-10 nN for typical cantilevers. Of

course, the force variation increases further for larger scan
sizes.

An alternative to the scanned-stylus AFMs described above
is described by Elings et al (U.S. Patent No. 5,025,658).
This design, shown in Fig. 2, places the AFM cantilever 14
extremely close to the emitting surface of a laser diode 21.
The laser light reflects off the cantilever, back into the
laser itself. The reflections will cause optical interference
that is detected at a photodiode 22 that is contained within
the laser package. Laser diode 21 are attached to scanner 12
using a laser mounting member 23. A miniature optical
interferometer is formed such that as cantilever 14 deflects
the amount of light detected at photodiode 22 changes. Since
the laser, photodetector, and the cantilever are closely
coupled, the laser and detector always tracks the cantilever,
independent of scan size.

This prior art system has a number of disadvantages,
however. First, this type of optical interferometer only has
sufficient sensitivity for AFM measurements if the laser and
cantilever are very closely coupled, typically with less than
100 micron separation. This requires extremely precise
alignment of the cantilever with respect to the laser.
Second, the piezoelectric translator must carry the weight of
a laser diode near the free end of the translator. This can
cause a reduction in the mechanical resonant frequency of the
translator, making the translator more susceptible to

vibrations. Also, because the laser is so close to the cantilever, it is not possible to view the cantilever and sample simultaneously with an optical microscope.

In addition, the optical interferometer used in the Fig. 2 AFM produces an output that changes periodically with distance. The position of cantilever 14 with respect to laser 21 is selected such that a deflection of cantilever 14 causes a change in the interferometer output. For example, the position could be selected so that positive cantilever deflections cause positive increases in the interference output. Then the force feedback will cause cantilever 14 to retract when the interference output increases. But because the interferometer output is periodic, sudden displacements of cantilever 14 can move it to a point where further deflections cause the interference signal to be opposite to that expected, i.e., decrease rather than increase. This sort of error will cause the feedback system to immediately jump the next period ("mode hop") of the interference signal. This makes accurate force control of the prior art scanned-stylus AFM of Fig. 2 very difficult.

Other versions of scanned-stylus AFMs have been built by Putman et al, *supra*, and commercial instruments have been produced by Topometrix, Inc. These designs are optical lever AFMs where the cantilever is scanned over a fixed sample. Both of these designs mount the laser and cantilever on the same scanning unit, so that they move together. This prior

art is shown schematically in Fig. 3. In Fig. 3 a focusing
lens 30 is disposed between laser 10 and cantilever 14. This
system has the disadvantage that scanner 12 has to carry the
weight of laser 10, electronic leads to laser 10, focusing
lens 30, and any mechanism for fine tuning the laser position
on cantilever 14. All of these can reduce the mechanical
resonant frequency of scanner 12 and transmit vibrations to
cantilever 14. Also, in the case of a tube scanner,
attachment of a laser to the interior of a scanner can make
its exchange difficult in case of laser failure.

In addition, these designs have the laser beam 17,
cantilever 14 and stylus 15 move with respect to a fixed
position sensitive detector 16. So when cantilever 14 is
scanned over the surface of sample 13, reflected laser beam 18
will move with respect to fixed position sensitive detector
16, even in the absence of any actual deflection of cantilever
14.

Other versions of scanned stylus AFMs have relied on
scanned optical fibers used as interferometers or as a moving
light source for the optical lever technique.

Another form of scanned-stylus AFMs use cantilevers that
are instrumented with a piezoelectric or a strain gauge
now U.S. Patent No. 5,266,801
(copending application serial no. 08/009,076 and Tortonese et
al, Transducers '91, 1991 International Conference on Solid-
State Sensors and Actuators, San Francisco, CA, 24-27 June
1991, and Tortonese et al, Appl. Phys. Lett., 62, p. 834,

(1993), and produce a voltage or a change in resistance that depends on the deflection of the cantilever.

A number of the prior art AFMS, especially those relying on optical interferometers to detect cantilever deflection, closely couple the cantilever and the laser light source and/or the assembly for detecting the cantilever deflection. In some cases this separation is less than 100 microns. This close coupling makes it extremely difficult to also view the cantilever and the area of the sample that it is scanning with an optical microscope.

SUMMARY OF THE INVENTION

It is an object of the present invention to provide a novel scanned-stylus AFM that detects cantilever deflection by reflecting a laser beam off the back side of the cantilever.

It is a second object of the present invention to prevent scanning the cantilever out from under a fixed laser beam.

Another object of this invention is to provide a scanned-stylus AFM that minimizes the tracking force variation across the entire scan range, and does not create artificially "warped" images.

A further object of this invention is to automatically provide a signal that is proportional to the motion of the cantilever across the sample.

Another object of this invention is to provide an AFM satisfying one or more of the above objects and can also operate with the cantilever and sample covered by fluid.

Still another object of this invention is to allow sufficient separation between the laser light source and the cantilever to provide access for an optical microscope to view the cantilever and the area of the sample that the cantilever is scanning.

These and other objects are achieved according to the present invention by providing a new and improved optical lever scanned-stylus AFM. The AFM includes a scanning mechanism, a fixed light source, a cantilever attached to the scanning mechanism, a stylus mounted on the cantilever and an optical assembly mounted on the scanning mechanism which guides a light beam emitted from the light source onto a point on the cantilever during movement of the scanning mechanism. A position detector receives a light beam reflected from the cantilever and detects a deflection of the cantilever. The optical assembly will move with the scanning mechanism and guide the light beam to a spot on the cantilever while it is scanned across the sample, to avoid both scanning the cantilever out from under a fixed, unguided beam and movement of the beam spot on the cantilever.

The optical assembly that causes the light beam to track the cantilever also provides a means of measuring the actual motion of the scan. A portion of the scanning light beam may

be directed to an additional position sensitive detector and the output of this detector can indicate the actual motion of the scanner. Since there may be differences between the desired motion of the scanner and the actual motion of the scanner, this technique provides a means to measure and correct the problem.

The scanning mechanism may comprise a piezoelectric tube scanner, where the optical assembly may also be mounted in the tube scanner. The scanning mechanism may be comprised of two or more different scanning elements, as mentioned in U.S. Patent 5,198,715. One or more of the scanning elements may have asymmetric cutaways that allow mechanical or optical access to the cantilever.

The AFM according to the invention may also include an optical mirror mounted for receiving a light beam from the light source, which may be at an arbitrary location, and directing the light beam to the scanning optical assembly.

The AFM may also include a separate optical mirror mounted to reflect light from the sample and cantilever to an optical microscope assembly. This arrangement makes it possible to directly view the cantilever and areas of interest on the sample. The mirror may be totally reflecting with a hole or it may be a partially reflecting or dichroic mirror to allow the light beam used to measure cantilever deflection to pass through the mirror.

According to the invention, the position detector may be located at a point where all light beams reflected from a cantilever with a fixed bend during a full extent of its movement converge.

This AFM according to the invention uses a light source, usually a laser, which is mounted so that it is not moved by the scanning mechanism, and an optical assembly using any combination of lenses, mirrors, or other optical elements attached to a scanning mechanism (or "scanner"). The motion of one or more of the optical components, attached to the scanner, guides the laser beam so that it always strikes a fixed point on the cantilever, and at a fixed angle with respect to the cantilever.

These and other objects are also obtained by a method of operating an AFM having a remote light source, a cantilever and an optical assembly attached to a scanning mechanism, and a position detector, including the steps of generating a light beam, directing the light beam onto the cantilever using the optical assembly so that the light beam strikes a substantially fixed point on the cantilever during movement of the scanning mechanism, and receiving a reflected light beam reflected from the cantilever using the position detector to detect a deflection of the cantilever.

The method may further take the steps of splitting the light beam into a first beam which strikes the cantilever and a second beam which is directed to a second position detector.

The method focuses the first beam to a point source between a fixed end and a free end of the scanning mechanism and then focuses an image of said point source on said cantilever. The method also allows the lateral position of the point source to be changed while maintaining a substantially fixed vertical position of the point source while scanning the scanning mechanism.

BRIEF DESCRIPTION OF THE DRAWINGS

A more complete appreciation of the invention and any of the attendant advantages thereof will be readily obtained as the same becomes better understood by reference to the following detailed description when considered in connection with the accompanying drawings, wherein:

Fig. 1 is a simplified functional block diagram of a prior art optical lever scanned-stylus atomic force microscope;

Fig. 2 is a block diagram of a prior art scanned-stylus atomic force microscope incorporating a laser diode interferometer;

Fig. 3 is a block diagram of a prior art atomic force microscope that scans the stylus and also the laser light source;

Fig. 4A is a simplified block diagram of an optical lever scanned-stylus atomic force microscope according to a first embodiment of the present invention;

Fig. 4B is a diagram of a tube scanner having an asymmetric cut out.

Fig. 5 is a modification of the first embodiment shown in Fig. 4, with the addition of a removable fluid cell allowing operation of the sample covered by fluid.

Fig. 6 is a modification of the first embodiment shown in Fig. 4, where the laser is mounted at the side of the scanner;

Fig. 7 is a simplified schematic diagram of a scanned-stylus atomic force microscope according to a second embodiment of the present invention;

Fig. 8 is a simplified schematic diagram of a scanned-stylus atomic force microscope according to a third embodiment of the present invention;

Fig. 9 is a modification of the third embodiment shown in Fig. 8, having multiple lenses;

Fig. 10 is a simplified schematic diagram of a fourth embodiment according to the present invention;

Fig. 11 is a simplified schematic diagram of a scanned-stylus atomic force microscope according to the invention illustrating the placement of the position sensitive detector;

Fig. 12 is a simplified schematic diagram of a first modification of the atomic force microscope shown in Fig. 11;

Fig. 13 is a simplified schematic diagram of a second modification of the atomic force microscope shown in Fig. 11; and

Fig. 14 is a flowchart of a method of operating the atomic force microscope of the invention.

DESCRIPTION OF THE PREFERRED EMBODIMENTS

Referring to the drawings, and more particularly to Fig. 4A, a first embodiment of the invention will be described. The AFM illustrated in Fig. 4 contains a light source 10, such as a laser, emitting a beam 41 which is directed through or alongside scanner 12. Scanner 12 is typically a piezoelectric translator, but could also be made of electrostrictive, magnetostrictive or other similar material. The scanner 12 is typically a tube translator, made of one or more piezoelectric tubes, as described in U.S. Patent 5,198,715, but could be of different shape and constructed of multiple scanning elements. A first lens 40 is disposed between the laser 10 and scanner 12, or attached to a fixed part of scanner 12. An optical assembly 43 is mounted on scanner 12 for guiding beam 44 onto cantilever 14. Preferably, the optical assembly 43 is mounted to the scanner using a mounting ring, which may be made of metal or an insulating material, or may be mounted using an adhesive. Optical assembly 43 can also be mounted on the exterior of scanner 12 and positioned such that beam 44 is guided onto cantilever 14. The AFM of Fig. 4A can also include a partially reflective mirror or a dichroic mirror 45 and optical microscope 46 for viewing cantilever 14 and sample 13. The mirror 45 may be attached to

the optical microscope 46, to the scanner 12 or mounting member 42, or to a separate fixed mounting structure (not shown). The beam 47 reflected from cantilever 14 is detected by position sensitive detector 16.

The cantilever 14 is attached to the scanner 12 via mounting member 42, and possible additional mounting elements (not shown). The additional mounting elements can allow the cantilever assembly to be exchanged for operation in fluid (U.S. Patent 4,935,090) or exchanged with probes for other scanning microscopes like the scanning tunneling microscope. The shape of mounting member 42 allows the beam 47 reflected from cantilever 14 to be detected, and allows other mechanical and optical access to cantilever 14. Parts mechanically similar to mounting member 42 made from metal or insulators have been used in the prior art, but, according to the present invention mounting member 42 is constructed from piezoelectric material and used as an actuator for the vertical, or Z direction. Note that the cut out on mounting member 42 need not be symmetric for the actuator to move substantially in the Z direction. Fig. 4B provides a more detailed view of the scanner 12 and mounting member 42, in particular the cut out which is labeled 42b.

For operation of an atomic force microscope where the sample 13 and cantilever 14 are covered by fluid, it is usually necessary to construct a fluid cell that presents a flat surface to incoming and outgoing light beams. One such

cell is shown in Fig. 5. This fluid cell 48 may be constructed of glass, plastic, or other transparent material. This fluid cell 48 is constructed such that at least the surfaces of the cell closest to the cantilever are at the same angle with respect to the incoming light beam 44 as is the cantilever 14. In this way, because of optical symmetry, the light beam leaving the fluid cell 47 will not change its angle when fluid 49 is added to fluid cell 48. It may be advantageous to have both surfaces of the fluid cell 48 be at the same angle as the cantilever 14. In addition, fluid cell 48 is removable and can be exchanged for mounting elements that are optimized for a contact AFM, oscillating probe AFM, scanning tunneling microscopes, or other scanning probe microscopes.

As cantilever 14 and stylus 15 are scanned over the surface of sample 13 the beam 44 "follows" the cantilever, i.e. the beam is incident on essentially a fixed spot on cantilever 14 during movement of cantilever 14. The movement of reflected beam 47 is detected by position detector 16. The problem of cantilever 14 moving out from under beam 44 is minimized or eliminated by using the motion of the optical assembly 43 attached to a moving part of scanner 12 (in this example the piezoelectric tube scanner) to guide beam 44 to always strike the same, or substantially the same spot on scanning cantilever 14. The changing position and angle of optical assembly 43 with respect to stationary incoming beam

41 can be used to bend beam 41 in a controlled way so that the
bent beam 44 always strikes the same or substantially the same
spot on cantilever 14 as it is scanned over sample 13. This
will occur if the position of the components of optical
assembly 43 is chosen such that the magnification of optical
assembly 43 matches the motion produced by scanner 12.

For example, consider the case where scanner 12 includes
an XYZ piezoelectric tube translator with an optical assembly
43 attached to the tube. If the tube translator is scanned
back and forth, the amount of translation of a point on the
tube depends on how far the point is from the fixed end (the
fixed end does not move, the free end moves the maximum
distance, and intermediate points move some fraction of the
maximum). If the optical assembly 43 is placed somewhere
between the fixed and free ends, it will move less than a
cantilever 14 placed at the free end. The optical assembly
may also be mounted in the interior of the tube so that the
light beam also propagates through the tube. The scanning
motion of optical assembly 43 will cause the light beam 44 to
move in a periodic way. Since optical assembly 43 will
typically move less than cantilever 14, optical assembly 43
must provide some optical magnification so that the output
light beam 44 will move the same distance as the cantilever
14. The moving optical assembly 43 will cause the light beam
to accurately follow the moving cantilever 14 if the optical
assembly 43 is located so that the optical magnification is

matched to a property that can be called the "mechanical amplification" of the scanner 12, or the ratio of the optical assembly 43 motion to the cantilever 14 motion. If the construction and position of optical assembly 43 are such that these magnifications are matched, the light beam 43 will track the moving cantilever 14.

Fig. 6 is a modification of the embodiment shown in Fig. 4. The light source has been positioned to the side of the scanner 12, and a mirror 50 has been mounted to direct beam 41 from the laser 10 through optical assembly 43 and onto cantilever 14.

A second embodiment of the invention is shown in Fig. 7. This AFM includes an optical arrangement incorporating two lenses. A first lens 60 is used to focus beam 61 to a point source 62 at an intermediate point on scanner 12. Lens 60 can be any of a variety of lenses, such as a convex lens or concave lens, so long as point source 62 is formed. Point source 62 could also be created by a diverging lens placed below the desired point source, by an illuminated pinhole, by an optical fiber, by a laser diode or other laser point source, for example. This embodiment also contains a mechanism for steering the light source 10 and/or lens 60 to move the point source 62 in the lateral direction. Moving the point source 62 also moves the position of the focused spot of light beam 68, allowing this beam to be adjusted for varying positions of cantilever 14. The steering mechanism is

constructed in such a way that while the horizontal position
of point source 62 may be altered, the vertical position, and
hence distance from lens 63, is essentially unchanged. Point
source 62 forms the object for a second lens 63 mounted to a
moving point on the scanner 12. The vertical position and the
focal lengths of both lenses are chosen so that the focused
image is formed at the cantilever 14. When cantilever 14 is
scanned, lens 63 will move laterally relative to the point
source object 62. This means that the focused image in the
plane of the cantilever will move laterally also. The
placement of the lenses can and has been determined by trial
and error, resulting in a successful design. Alternatively, a
suitable lens position can be computed by the following
procedure, involving standard optical calculations. Some
simple example calculations are listed below. It may of
course be necessary to take into account various optical
aberrations, not discussed here. (see, for example, Hecht and
Zajac, Optics, 3rd Ed., Addison-Wesley, Menlo Park (1976)).

If the steering lens 63 is moved perpendicular to the
optical axis with respect to the point source object by a
distance Δo, the focused image will move by a distance Δi.
The distance Δi is the sum of the lens motion Δo plus
additional motion due to the magnification of the optical
system. Specifically, $\Delta i = \Delta o + M_l \cdot \Delta o$. Here the optical
magnification of the lens system M_l is given by y_i/y_o, where y_i
is the distance between the lens and the focused image on the

cantilever, and y_0 is the distance between the lens 63 and the point source object 62.

For a given motion of scanner 12, cantilever 14 moves a distance Δc with respect to the point source 62 that is greater than the lens 63 motion Δo. The ratio of the cantilever motion Δc to the lens motion Δo may be called the mechanical magnification of the scanner M_s. This factor M_s depends on the position of the steering lens 63 and the cantilever 14 with respect to each other and with respect to the scanner 12. This quantity may be calculated theoretically, or measured for a given scanner by a variety of means. It is necessary to arrange the magnification M_l of the lens so that the motion of the focused image Δi is approximately the same as the cantilever motion Δc. In this case the focused spot of light beam 68 moves the same distance as the cantilever 14 as it scans over the sample. Thus, the light beam 68 is incident on a fixed spot on cantilever 14 throughout its motion of scanning.

In the case where $\Delta i = \Delta c$, the optical magnification M_l and the mechanical magnification of the scanner M_s are related in the following manner:

$$M_s = \Delta c/\Delta o = \Delta i/\Delta o = (\Delta o + M_l \cdot \Delta o)/\Delta o = 1 + M_l$$

The choice of lenses and their positions may be determined by trial and error or with the above equations. It should be noted that there are a whole family of lens and position sets that will give satisfactory results. In

addition, while the above calculations define sets of lenses
and positions that will satisfy one or more objects of the
invention, it may be possible to arrive at other lens
combinations placed at a variety of positions that accomplish
substantially the same task, that is, using an optical
assembly moved by the scanner to make the light beam track the
cantilever throughout its motion of scanning. It is of course
possible and potentially desirable to add other lenses or
other optical components to direct the path of light beams 61,
68, 47, or 67, or to reduce various optical aberrations.

Fig. 7 also shows an optional beam splitter 65 and
additional position sensitive detector 66 that may be used to
measure, calibrate, or control the motion of scanner 12. The
optical elements shown in Fig. 7, along with the motion of
scanner 12, create a moving light beam 68 to follow cantilever
14 when scanning. A portion 67 of light beam 68 may be
directed by beam splitter 65 to an additional position
sensitive detector 66. Laser beam 67 will automatically move
on position sensitive detector 66 in proportion to the motion
of scanner 12. Since piezoelectric translators, commonly used
as AFM scanners, suffer from nonlinearities, drift, and
hysteresis, it is desirable to measure and correct for these
distortions. By measuring the position of laser beam 67 on
position sensitive photodetector 66, it is possible to measure
the position of scanner 12 in real time. This signal then can
be used to calibrate the scanner drive signals to create

linear scans, as described in U.S. Patent No. 5,051,646, to correct AFM data after it has been stored, or to use a feedback system to correct for scanner distortions in real time. Using laser beam deflections to correct for piezoelectric scanner distortions has been described by Marshall in U.S. Patent No. 5,172,002.

Fig. 8 shows a third embodiment of the invention that uses a single lens. In this design a parallel laser beam 70 is focused onto a cantilever using a steering lens 71 mounted close to the free end of a scanner. In practice, lens 71 is mounted at least 70% of the distance from the fixed end of the scanner 12 to the cantilever 14. Focussing the parallel beam allows the focused spot to follow the center of the lens. Lens 71 moves almost the same distance and angle as the cantilever. Since the parallel rays of the parallel light beam 70 will focus at a point a fixed distance below the center of lens 71, moving the lens with the cantilever will cause the focused laser spot to track moving cantilever 14. The performance of this embodiment is determined by how close lens 71 can be placed to cantilever 14 in practice. As lens 71 is placed farther from cantilever 14, it will not move as far as cantilever 14 and the tracking accuracy will decrease. This steering lens could also be used as the objective in a optical microscope, allowing optical viewing of the cantilever 14 and sample 13.

Fig. 9 shows another alternative optical arrangement,
that is a variation of the AFM shown in Fig. 8. In this
arrangement a fixed lens 80 is placed above steering lens 71.
Fixed lens 80 weakly focuses the beam emitted from light
source 10 before it reaches the steering lens. The lenses and
their positions are chosen by standard optical calculation
where the focal length f_1 of fixed lens 80 is much longer than
the sum of focal length f_2 of steering lens 72 and the
separation between lenses 72 and 80. The focal length f_2 is
chosen so that it focuses the light beams from lens 80 to a
spot on cantilever 14. This accomplishes two things. First,
it allows the size of steering lens 71 to be smaller, and
hence the weight to be less. It is desirable to minimize the
weight that scanner 12 must carry to maintain a high
mechanical resonant frequency and thus immunity from
vibration. Second, fixed lens 80 may be chosen to offset or
reduce coma errors introduced at steering lens 71 due to the
fact that the angle of lens 71 with respect to the incoming
light beam changes as scanner 12 moves steering lens 71 and
cantilever 14.

A fourth embodiment of the invention is shown in Fig. 10.
In this embodiment, the parallel beam 91 emitted by laser 10 is
focused so that a spot will result on the cantilever. A
steering mirror 90 is placed at a point on scanner 12 so that
the translation and angular swing of mirror 90 always guides
the laser beam to a moving cantilever. A single mirror could

be used for single axis scans, two mirrors could be used for complete two axis scans. A single mirror is shown for clarity. The required position of the mirror 90 will depend on the construction details of scanner 12, but the appropriate position can be found very simply by trial and error. This may be done by varying the position of the mirror 90 with respect to the cantilever until the light beam reflected off the mirror 90 accurately tracks the cantilever 14 throughout its scanning motion.

Since the embodiments shown in Figs. 8-10 also create a light beam that moves in proportion to the scanner motion, this light beam motion can be used to measure, calibrate or correct the scanner motion as shown in Fig. 7 and described above, i.e., a beam splitter and second position detector could be added.

All of the embodiments described above allow sufficient clearance (up to several inches) between the light source 10 and the cantilever 14 to allow access for an optical microscope. As mentioned, some of the lenses or optical elements used for causing the laser to track the cantilever could be used as part of the optical microscope.

The present invention also provides large scans with uniform tracking forces over the entire scan. As mentioned previously, as cantilever 14 is scanned over a sample 13, both the position and angle of cantilever 14 with respect to a fixed position sensitive detector 16 will change. In the

prior art, this caused the reflected laser beam to move on the position sensitive detector, mimicking an actual deflection of the cantilever. These "false deflections" present in prior art AFMs, which were described by Baselt et al, supra, distort images with "bowing," i.e., flat surfaces appear curved. In addition, the feedback system is programmed to keep the position of the reflected laser at the position sensitive detector constant. It will read these "false deflections" as real deflections and adjust the actual deflection of the cantilever to compensate for the errors. Adjusting the actual deflection of the cantilever, changes the tracking force exerted by the cantilever stylus. For many samples, it is necessary to minimize the tracking force to avoid damage to the surface (Hoh and Hansma, *supra*). The changing tracking force introduced by the prior art AFM makes it impossible to reduce the tracking force to less than the amount that it changes over the scan. In practice, the resultant tracking force may be much larger than delicate samples can withstand. The present invention solves this problem in two ways. First, as described above, ensures that the light beam strikes essentially the same spot on the cantilever as the cantilever is scanned over the surface. This minimizes or eliminates "false deflections" that are caused by variations in the bend of the cantilever as discussed by Baselt, *supra*. It also ensures that there are no "false deflections" due to the cantilever being scanned out from under the light beam.

Secondly, minimizing spurious force variations and eliminating "warped" images is detailed below. For optimal performance, techniques shown in Figs. 5-10 are intended to be used in combination with one or more of the techniques shown in Figs. 11-13 and described below.

Fig. 11 shows a fifth embodiment of the invention directed to solving the problem described above. In this embodiment, the incoming light beam 101 tracks the moving cantilever 14 by one of the means shown in Figs. 7-10, or by any other similar means. Now as cantilever 14 scans over the surface of sample 13, both the position and angle of the reflected beam 102 change. In Fig. 11, three different incoming (101) and reflected (102) laser beams are shown, corresponding to three different positions of cantilever 14. As the cantilever 14 scans over surface 13, the angle of the cantilever 14 with respect to the position sensitive detector 16 changes in a predictable and reproducible way. The light beams 101 and 102 are shown schematically as thin lines for clarity, but are actually focused to a small spot onto the cantilever 14 and diverge to the position sensitive detector 16 at point 104 as shown in Figs. 5-10.

From Fig. 11 it is clear that there is a position in space that all of these reflected laser beams 102 converge, provided that the angle traced out by the scanner 12 is small (in practice, the angles traced out are much less than one degree; the angles shown in Fig. 11 are approximately ± 5

degrees). This convergence can be understood in the following way. As the cantilever 14 is scanned over surface 13, the angle of the cantilever 14 with respect to position sensitive detector 16 will change slightly. For example, in Fig. 11, as cantilever 14 is scanned to the left, the angle of cantilever 14 will become shallower, and as cantilever 14 is scanned to the right the angle gets steeper. If one were to plot the angle of cantilever 14 over its entire scan range, the result would be a surface with a slightly convex curvature. The degree and type of curvature of this surface depend on the details of the motion of the scanner 12. In some cases it may be sufficient to consider this surface as a part of a sphere where the radius is given by the distance between the cantilever and the apparent pivoting point of the scanned motion. This convex surface formed by the scanning cantilever 14 will act like a convex mirror of the same curvature. For this reason, this convex surface acts in a way that will focus all reflected beams from a point source 100 to another point, for example the point of convergence 104 shown in Fig. 11. The point at which the beams converge can be determined by geometric construction, or by calculation from standard optical formulas for convex mirrors (see, for example, Hecht and Zajac, *supra*). If position sensitive detector 16 is placed at or near the focus created by the traced out concave surface, the AFM will be insensitive to the motion of cantilever 14 caused by the scanner 12.

In this embodiment, the position sensitive detector 16 is placed at the point of convergence 104. If position sensitive detector 16 is placed near point of convergence 104, similar results may be obtained, but optimal precision is obtained at point of convergence 104. In this case, the changing angle and lateral position of cantilever 14 no longer moves the reflected laser beam 102 on position sensitive detector 16. In this way "false deflections" are eliminated. Also in practice it is not necessary to determine curvature of the surface created by the scanning cantilever. Instead it is possible to empirically determine the optimum position of the position sensitive detector 16. This is done by scanning the cantilever on a very flat surface or actually not touching any sample, and measuring the change in the position of the signal from the position sensitive detector. The amount of change in this signal is a measure of the amount of "false deflection" being seen by the system. The position sensitive detector may be moved closer or further from the cantilever until these "false deflections" are minimized. It is also possible with this technique to eliminate apparent curvatures that appear because of the pendulum-like motion of the scanner.

Fig. 11 also shows an alternate embodiment where an optional mirror 103 is used to redirect portions 106 of the reflected laser beams 102 so that the point of convergence occurs at another position. This allows the position

sensitive detector 105 to be put in a more convenient location.

Fig. 12 shows a modification of the embodiment of Fig. 11 where a relay lens 110 is used to transfer the point of convergence to another more convenient position. Lens 110 may also be used for adjusting the size of the reflected laser beam 102 so that it is optimized for the position sensitive detector 16. It is of course possible to use other lenses using standard optical practice to adjust the rate of convergence of beams 102 to make the convergence point 104 occur at other desired locations. A mirror could also be used in this embodiment anywhere between the cantilever and the position sensitive detector in the same manner as shown in Fig. 11 to direct the point of convergence to a different position.

Fig. 13 shows an alternate embodiment that uses a single concave mirror 120 to redirect the point of convergence shown in Figs. 11-12 to a more convenient position. In this case the single concave mirror 120 replaces the flat mirror 103 shown in Fig. 11 and the relay lens 110 shown in Fig. 12.

A method of operating the AFM according to present invention will now be described. As shown in Fig. 4A, for example, a light beam is generated and then directed onto cantilever 14 using optical assembly 43 so that the light beam strikes substantially a fixed point on cantilever 14, during movement of the scanning mechanism. The striking of

substantially a fixed point is illustrated in Fig. 13, where
light beams 101 strike cantilever 14 while it is scanned
across sample 13.   The light beam reflected from cantilever 14
(47 in Fig. 4) is received by position detector 16 which can
detect deflections of cantilever 14.

Also illustrated in Fig. 4A is the splitting of beam 44
using splitter 45 and the cut out in mounting member 42 (Fig. 4B) to
allow access of an optical microscope 46, while in Fig. 7 the
beam 68 is split using splitter 65 to direct a portion of the
the beam 68 to a second position detector 66.

Fig. 14 is a flowchart of a modification of the method of
the invention where the location of the position detector is
determined. First, in step 14-1, the light beam reflected
from the cantilever is measured while the scanner 12 is
scanned over a full extent of its movement on a very flat
surface or while actually not touching any sample. The change
in position in the measured signal is then determined using
position sensitive detector 16 (step 14-2). The amount of
change in this signal is a measure of the amount of "false
deflection" being seen by the system. The position sensitive
detector is then moved closer or further from the cantilever
(along the optical axis of the reflected beam) and the
scanning process repeated (step 14-3) a desired number of
times until these "false deflections" are minimized (step 14-
4). Position detector 16 is then placed at this location of
minimum change (step 14-5).

While the invention has been described with reference to several specific embodiments, those skilled in the art will be able to make various modifications to the described embodiments without departing from the true spirit and scope of the invention. For example, an AFM that scans using other optical elements such as prisms instead of lenses or mirrors, or other combinations of such elements to keep the laser focused on a scanning cantilever, is within the intended scope of the invention. It is therefore to be understood that the within the scope of the appended claims, the invention may be practiced other than as specifically described herein.

Although what has been described is a contact AFM, where the stylus is in constant contact with the surface, the described invention can also be used in applications where the cantilever is oscillated, such as magnetic force microscopy (Martin and Wickeramasingle, Appl. Phys. Lett., 50, pg. 1455 (1987), Non-contact Topography, Durig et al, Phys. Rev. Lett., 53, p. 1045, (1988)) and as a jumping probe microscope where the stylus is repeatedly lifted off the surface during a scan (U.S. Pat. Application 08/009,076). now U.S. Patent No. 5,266,801